Modeling Dynamic Vehicle Navigation in a Self-organizing, Peer-to-peer, Distributed Traffic Information System

Xu Yang, Will Recker

Institute of Transportation Studies
University of California Irvine

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Xu Yang and Will Recker
Institute of Transportation Studies
University of California, Irvine, CA 92697, USA

Abstract
This paper presents a simulation-based framework to model the potential benefits from dynamic vehicle on-line routing in a self-organizing, distributed traffic information system based upon a vehicle-to-vehicle information-sharing architecture. Within this framework, certain vehicles with specific inter-vehicle communication equipment in the traffic network capable of autonomous traffic surveillance and peer-to-peer information sharing, independently optimize their routes based on real-time and historical traffic information, forming a self-organizing traffic information overlay to the existing vehicular roadway network. In-trip re-routing decisions arising from drivers' accessing the self-organizing information system are modeled according both to a rational-boundary model and to a binary-logit model under the assumption that each driver is a rational entity. A path-based microscopic traffic simulation model is developed to study on-line vehicle navigation in the proposed distributed traffic information system, testing non-recurrent congestion cases on two different large-scale networks representing typical roadway scenarios in daily commuting. Based on simulation study results, potential benefits both for travelers with access to the proposed traffic information system as well as for the traffic system as a whole are demonstrated.

1. Introduction

The potential benefits and drawbacks accruing from advanced traffic information systems (ATIS) have been addressed by many researchers, using both analytical approaches (Ben-Akiva et al., 1991) and simulation approaches (Mahmassani and Jayakrishnan, 1991). Limited field testing of such systems has been conducted in such projects as ADVANCE (Boyce et al., 1994) and PROMETHEUS (Zimmer et al., 1994) to study for ATIS in large-scale networks. However, virtually all of the traffic information systems either investigated (mostly through simulation) or deployed have been centralized systems (Bacelo et al., 1999).

Similarly, within the automotive telematics industry, currently all commercialized traffic information systems are centralized systems, either integrated within an in-vehicle navigation system or as a stand alone system. These systems all require a centralized traffic information center (TIC) to process traffic information typically derived from data collected from fixed detection stations installed in the roadways connected to the TIC via wired cable or from "floating-car" data polled from vehicles connected to the TIC via wireless modem, and then the processed data distributed to their users via wired or wireless communication connections. Shortcomings of these centralized information systems include: heavy capital investment is needed to initiate the system, difficulty of system upgrade, vulnerability to system failures, and general lack of specific relevancy of information provided to any particular trip.

With the development of information technologies, especially those associated with inter-vehicle communication (IVC), the potential for distributed traffic information systems has gained interest both in the transportation academic community (Ziliaskopoulos and Zhang 2003, Recker and Yang 2004) as well as in industry where some initial field studies were also tested (Franz et al., 2001). More recently in the US, Ford Motor Company announced in February 2004 that it was pursuing "the next-generation travel advisory system" by turning "vehicles into mobile traffic-monitoring tools" (Rajiv Vyas, Detroit Free Press, February 27, 2004). And, efforts to establish the Integrated Network of Transportation Information (INTI), currently being pursued by the Intelligent Transportation Systems Joint Program Office of USDOT, offer the promise of "simultaneous conversations among vehicles" supported by Dedicated Short Range Communications (DSRC) technologies. In contrast to centralized systems, distributed traffic information systems based on information exchange among vehicles do not require any public infrastructure installed in the network; rather, they rely only on on-board devices installed in at least some vehicles traversing the roadway network. Because such systems are totally independent of public infrastructure, they will be market-driven and self-maintained, without the noted shortcomings of centralized systems. Vehicles in the traffic network generate information, exchange information, process information, and distribute information; they are not only the users (passive beneficiaries) of the system, but also information sources (active contributors) to the system.

The "information wave" resulting from instantaneous uni-directional and bi-directional information propagation via peer-to-peer information exchange among IVC-equipped vehicles in the network (Jin and Recker, 2004) and non-instantaneous bi-directional information propagation (Ziliaskopoulos and Zhang 2002) in linear traffic networks under both incident-free and incident conditions have been studied using analytical approaches. Simulation approaches were used more widely to test information propagation in one-dimensional traffic networks (Recker and Yang, 2004) and two-dimensional traffic networks both for incident-free (Yang, 2003) and for incident cases (Ziliaskopoulos and Zhang 2002, Yang, 2003).

Recker and Yang (2004) have performed simulation studies for online IVC-capable vehicles' re-routing under incident conditions in a freeway corridor network. Using a simple re-routing rule followed by vehicles with IVC capabilities to be diverted from the freeway to the arterial streets to avoid the incident spot on the freeway after receiving incident and link travel time information packets, results from their simulation testing show that there are potential benefits both for travelers with IVC equipment and for the traffic system as a whole, especially under no-recurrent congestion traffic conditions.

Although inter-vehicle communication and information dissemination in traffic networks have been modeled both from various academic perspectives (transportation engineering, electronic engineering and computer science) and at different levels (highly abstract, software protocols and hardware products), no efforts have been found that systematically model and test such a distributed traffic information system based upon peer-to-peer information exchange relative to drivers' dynamic on-line routing behaviors within it. This paper focuses on detailed modeling of a self-organizing, distributed traffic information system built upon vehicle-to-vehicle information exchange, with case testing of the pre-trip route-choice and in-trip re-route behaviors of drivers with access to traffic information from the proposed information system. Two different large-scale traffic networks, one comprising grid arterial streets and the other a freeway corridor, are tested with respect to different assumptions regarding drivers' route choice behavior (including both pre-trip route choice and in-trip re-route behaviors) and different levels of knowledge of daily recurrent traffic patterns. Potential benefits arising from this proposed information system both for travelers with IVC and for the whole traffic system including all travelers with and without equipment are demonstrated based on simulation study results.

The remainder of this paper is structured as follows. In the next section, detailed descriptions of the modeling framework for studying IVC-capable vehicle dynamic on-line routing in the proposed self-organizing, distributed traffic information systems is presented, including the modeling of software process, hardware abstraction, and human behavior. In section 3, simulation implementations for dynamic vehicle on-line navigation for two different networks are presented in detail, and potential benefits from the distributed traffic information system are addressed based on analysis of the simulation results. The final section summarizes the findings and conclusions of this paper and presents suggestions for future modeling efforts.

2. Modeling framework
In order to study dynamic on-line routing behavior within this complex system, the interactions among many components need to be modeled, including those between vehicles and roadway networks, those among vehicles with peer-to-peer communication capabilities, and interaction of drivers with their received traffic information. Due to extremely complicated relationships among these components, a micro-simulation approach was adopted to analyze information-sharing among vehicles via peer-to-peer communication within the traffic network.

Within the micro-simulation modeling framework, some vehicles in the traffic network, equipped with IVC systems, geographic information systems (GIS), global positioning systems (GPS), on-board navigation systems, and in-vehicle computing processors, are assumed to generate floating car data information based on their own experiences, exchange traffic information through peer-to-peer communications, and process incoming traffic information in real-time using their on-board processors. In addition, each vehicle within this distributed traffic

information system is assumed to optimize its personal route based on its estimation of current traffic conditions obtained from real-time traffic information propagated in the information network (if so equipped) and its understanding of recurrent traffic pattern from its historical traffic information database; based on the assumption that each driver is a rational entity, re-routing decisions are examined according to 1) rational-boundary model, and 2) binary-logit model. Vehicles with IVC capability in this self-organizing information system can dynamically navigate the roadway networks, following changeable paths based upon their re-routing decisions; vehicles without such equipment only move in the traffic network following the fixed route decided before their departure. Figure 1 shows simulation modeling procedures for vehicles and drivers with cooperative equipment (GPS, GIS, IVC, on-board computer and in-vehicle navigation system) both before and during their trips. Simulation modeling procedures for vehicles without such equipment are shown in Figure 2. The detailed descriptions for each modeling procedures in our simulation framework are presented in following sub-sections.

2.1 Historical traffic information database

For comparison purposes, building an historical traffic information database for travelers to determine (either implicitly or explicitly) a planned route before they physically begin their trips was accomplished using two approaches: 1) random-arbitrary method, and 2) experience-average method.

In the random-arbitrary method, link travel times are calculated based on free flow traffic conditions with modifications considering signal impacts and random errors; this assumption thought to apply to situations in which little or no experiential historical information is available, e.g., for newly constructed networks or for drivers unfamiliar with the network but who have had experience with similar choices. Equation (1) shows the calculation of link travel time for a given link based on random-arbitrary method.

$$H_i = \frac{L_i}{S_i} \cdot (1 + \alpha \cdot \Delta) \tag{1}$$

where H_i is the calculated historical link travel time for link i, L_i is the length of link i,

S_i is the free-flow speed on link i, Δ is a random variable (based on a specific random seed) whose value is between 0 and 1, and α is a sensitivity parameter modifying the random effects. For demonstration purposes, results were obtained for two values of α, $\alpha = 0.5, 1.0$.

In the experience-average method for generating historical link travel time information in our simulation modeling framework, each vehicle's experienced (simulated via microscopic simulation) link travel time information for each individual link for the studied time period (divided into many time intervals) under both non-congested and re-current congestion conditions was recorded for many different days, then the average link travel time based on all (simulated) experiences from different days for same time interval for each individual link in the traffic network are calculated as the historical link travel time information for that specific time interval and stored in the historical database. Equation (2) shows this link travel time calculation for a specific time interval for an individual link. The average values of each link travel time for whole studied time period are also calculated as shown in Equation (3) and stored in the historical database.

$$H_{ij} = \frac{1}{n} \sum_{k=1}^{n} R_{ijk} \qquad (2)$$

$$H_i = \frac{1}{m} \sum_{j=1}^{m} H_{ij} \qquad (3)$$

where H_i is the historical link travel time for link i during the study period, H_{ij} is the calculated historical link travel time for link i in time interval j, based on experience-average method, R_{ijk} is average value of all recorded vehicle travel times for link i in time interval j for the k_{th} simulation run (based on k_{th} random seed in the simulation), m is the number of time intervals into which the study time period is divided and n is total number of simulation runs under various random seeds for the same O/D demand and test network. The experience-average method is thought to mimic the real-world experience, in which historical traffic information is gleaned from the compilation of daily commute experience (trials).

2.2 Pre-trip route optimization and route choice behaviors
It is assumed that all travelers optimize their routes based on the same historical traffic information before their trips begin, under the assumption that each individual traveler has equal opportunity to access the historical traffic information database to understand the traffic patterns under congestion-free and re-current congestion conditions in their pre-trip planning phases. That is, drivers with IVC capability do not have any extra information compared to drivers without IVC capability, and their pre-trip route choice behavior follows the same patterns as drivers without IVC capability.

In the case of the random-arbitrary method to generate historical link travel time information, two different group random seeds are used to give two groups of values of travel time for each individual link in the networks, and two shortest paths are calculated for each origin-destination pairs based on these two groups of link travel time values using the Floyd-Warshall algorithm (Floyd, 1962). Under these conditions, each driver has two possible choices of shortest routes from its origin to its destination; a binary-logit model is used to choose one route for each driver from these two possible choices (Equation (4)).

$$P_j(1|r_j,s_j) = \left(1 + e^{\theta \cdot \Delta TT_{rs}}\right)^{-1}$$
$$\Delta TT_{rs} = \left[TT_{rs}(1) - TT_{rs}(2)\right]/TT_{rs}(1) \qquad (4)$$

where $P_j(1|r_j,s_j)$ is probability of driver j taking path 1 from its origin r to destination s,

θ is a constant parameter, $TT_{rs}(1)$ is total travel time for shortest path 1 from origin r to destination s based on link travel time values from 1st group random seeds, and $TT_{rs}(2)$ is total travel time for shortest path 2 based on link travel time values from 2nd group random seeds.

In the case of the experience-average method to generate link travel time values for the historical traffic information database, the shortest paths for each origin-destination pair are calculated based on the values of each individual links' travel time for the whole studied time period in the

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database. All drivers choose these calculated shortest paths as their initial paths from their respective origins to destinations.

Regardless of which model is used for drivers' initial route choices in their pre-trip planning stages, drivers with IVC capabilities may change their routes at any time during their trips based on their reevaluation of the network traffic conditions from real-time information through peer-to-peer information exchange; however, drivers without IVC capability are restricted to follow the routes that they choose before trips begin. Details of the implementation of pre-trip route optimization and the rationale for selection of the initial route choice model for each individual test case are discussed in next section.

2.3 Path-based vehicle navigation
To study IVC-capable vehicle on-line routing, a path-based micro-simulation platform was developed, in which each individual vehicle is represented as an entity traveling in the traffic network, following either the exact route it chose in pre-trip planning phase or a revised route based on re-routing decisions made during its trip, until arriving at its destination. Each IVC-capable vehicle traveling in the roadway network stores its own path that is changeable at any decision point when approaching the ending node of current link it is traveling on; the vehicle makes a decision for its next turning movement (left-turn, right-turn or go straight ahead). In addition to the stored historical link travel time of each link in the network, vehicles with IVC capability store a dynamic electronic map consisting of their most current traffic information for these links, and continually update real-time traffic information in its own map based upon information transmitted from other IVC-capable vehicles within communication range. IVC-equipped vehicles are thus capable of dynamically navigating in the traffic networks, changing their routes during trips based on estimations of the latest traffic conditions, compared to non-IVC vehicles that are capable only of static navigation in roadway networks, following fixed routes based only on decisions made before starting their trips using historical traffic patterns.

2.4 En-route traffic information generation
In the self-organizing distributed information system being analyzed, IVC-capable vehicles traveling on the roadways act as intelligent sensors that evolve a real-time picture of conditions in the traffic network through peer-to-peer information exchange. These vehicles continually poll other such vehicles in the traffic network, collecting raw traffic information data in real-time based both on their own traveling experiences, as well as those of the vehicles polled. As each IVC-capable vehicle traverses a network link, it generates a "link-based" information packet (Yang, 2003) as shown in Table 1 representing the link travel time experienced for that specific link, which then is placed in a buffer that may be probed by other vehicles.

Table 1. Link-based information packet format

Variable name	Detailed representations	Size
Vehicle ID	ID # of the vehicle which originally generated this information packet	16 bits
Message time stamp	Time when this information packet was originally generated by the generating vehicle	32 bits
Vehicle GPS location	Vehicle GPS location coordination (X, Y) when it originally generated this information packet	32×2 bits
Vehicle speed	Vehicle speed when it originally generated this information packet	32 bits
Link ID	ID # of link passing through when it originally generated this information packet	16 bits
Link travel time	Vehicle travel time for the link represented by Link ID	32 bits

There are two different modes for IVC-capable vehicles to sample roadway traffic conditions based upon their own experiences by generating link-based information packets: link basis mode and time basis mode. In link basis mode, a vehicle with IVC equipment calculates link travel time from its own full experience of this specific link and generates a link-based information packet for that link when it reaches the end of the link it is just traveling on. In time basis mode, a vehicle with IVC capability estimates link travel time for the link it is still traveling on based on its partial experience for that link (extending this partial experience to the whole link) and generates link-based information packet for this specific link every certain time interval which could be easily defined and changed as a parameter in the simulation practices.

In our modeling framework for IVC-capable vehicle dynamic on-line routing, at specific time intervals after entering a specific network link, each IVC-capable vehicle estimates link travel time for the link it is traveling on based on its partial experience for that link (extending this partial experience to the whole link) and generates a link-based information packet for this specific link; upon reaching the end of a link, it calculates link travel time and generates a link-based information packet based on its full experience. In this way, under congested traffic conditions in which vehicles may take an extended period of time to traverse a given link, updated conditions on that link will be guaranteed to be generated at intervals no greater than the sampling rate. In the simulations reported here, each IVC-capable vehicle generates a link-based information packet for the link it is traveling at one-minute intervals after entering the link, and generates a link-based information packet based on its full experience upon leaving the link.

2.5 Inter-vehicle communication modeling
After link-based traffic information packets are generated by vehicles with the specific equipment according to the specific sampling policy, they are available to be passed to other vehicles with IVC capability. Vehicle-to-vehicle communication is modeled at a highly abstract level, namely that neighboring IVC-capable vehicles have opportunity to exchange necessary information with each other if the physical distance (D) between them is less than a pre-defined parameter – communication radius range (R); no consideration is given to any specific inter-vehicle wireless communication technologies or to any complications arising from the relative

speed between these two vehicles during their communication process. Figure 3 shows several different vehicle movements and network geometric scenarios considered.

During each communication cycle, each IVC-capable vehicle gets link-based information packets from its neighboring IVC vehicles if their communications are successful, then compares these newly received packets with packets received from other IVC vehicles during previous communication processes and already stored within its communication buffer. If the time stamp of a newly received packet for a specific network link is more recent than the time stamp of the previously received packet, the new information packet is combined with any current link travel time information from the IVC-capable vehicle's own perspective (in its own information processing buffer) to estimate real-time traffic conditions more accurately for the link; it then stores the packet in its communication buffer to be broadcast to other IVC-capable vehicles in next communication cycle. In this way, each IVC vehicle needs only to maintain the newest packets for each link in the traffic network in its communication buffer, while still maintaining the capability to estimate current traffic conditions based not only on these newest information packets but also link travel time information within the information processing buffer that implicitly integrates all previously received information.

2.6 Real-time traffic information processing

The raw travel time information generated by each IVC-capable vehicle needs to be appropriately processed by each individual IVC vehicle bettering order to estimate current traffic conditions from its own perspective. Owing to variations in the distribution of IVC-capable vehicles in the network, speed distributions of IVC-capable vehicles and geometry of the roadway network, even two very close individual IVC vehicles (in space domain) at the same time (in time domain) in the traffic network may have a totally different understanding of the current traffic situations after processing raw link-based information packets from their own points of view.

In the simulation, a modified exponential filter as shown in Equation (5) was incorporated in each IVC vehicle to smooth estimates of link travel time values as new raw link-based information packets are received. Owing to the nature of the irregularity in the timing of reception of information packets from other vehicles (relative to current time), dynamic smoothing factors in our modified exponential filter are calculated based on differences between time stamp in the most recent packet to be used in this smoothing cycle and the time stamp of the last stored packet (i.e., the most recent up to that particular time) for the same link (See Equation (6)). If this time difference is more than a pre-specified threshold value (15 minutes is used in the cases reported here), only the newly received packet is considered in the smoothing filter to compute the estimation of link travel time for that specific link. The smoothed values of link travel time for every link in the traffic network are stored in each IVC vehicle's information processing buffer and are used as primary source for link travel time values (with historical link travel time values as backup values) in dynamic shortest path calculations for each IVC vehicle.

$$ST_i = K_i \cdot NT_i + (1 - K_i) \cdot ST_{i-1} \tag{5}$$

$$K_i = \begin{cases} 1; \ t_i^{new} - t_i^{old} > t^* \\ -0.5 + 0.5 \cdot (t_i^{new} - t_i^{old})/t^*; \ t_i^{new} - t_i^{old} \le t^* \end{cases} \tag{6}$$

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where

ST_i is the smoothed link travel time value for link *i* in the current cycle *t*,

ST_{i-1} is the smoothed link travel time value for link *i* in previous smoothing cycle *t*-1,

NT is the raw link travel time value for link *i* in the newly received link-based information packet whose time stamp is newer than the last previous,

K_i is the smoothing factor for link *i* in the current smoothing cycle *t*,

t_i^{new} is the time stamp of the newly received link-based information packet for link *i*,

t_i^{old} is the time stamp of the link-based information packet last previously received and used in the last smoothing cycle for link *I*, and

t^* is a parameter (15 minutes in the results shown in this paper).

2.7 En-route route optimization and re-route behaviors

Once processed on-board, the raw link-based information packets obtained via peer-to-peer communications provide IVC-capable vehicles with updated knowledge of current network traffic conditions. From this real-time link travel time information stored the vehicle's processing buffer, each individual IVC-capable vehicle can find the shortest path from its next decision point (the ending node of current link this vehicle is traveling on) to its destination point using, for example, Dijkstra's algorithm (Dijkstra, 1959). Historical link travel time information, drawn from historical traffic information database within the vehicle, for those links for which real-time information is not available (typically because either IVC market penetration rate is low and/or IVC communication radius is short) is used to substitute the real-time link travel time values in shortest path algorithm implementations. (In the simulations reported here, historical link travel times were substituted for the estimated current link travel time value stored in IVC-capable vehicle's processing buffer when the latest estimation of a particular link lags the current time by 15 minutes or more.)

The computed shortest path based on the most recent information is compared to current path, and any re-routing decision is made according to the re-routing behavior models within our simulation framework. Two re-routing models are implemented in our simulation—the so-called rational-boundary model (Mahmassani and Jayakrishnan, 1991) and a binary-logit model (Ben-Akiva, 1985). In the case of the rational-boundary model, shown in Equation (7), an IVC-capable driver is assumed to re-optimize the current route either when the relative difference travel time between two paths is larger than a pre-defined relative threshed parameter or when the absolute difference between these two paths is higher than a pre-defined absolute threshold.

$$\delta_j(k) = \begin{cases} 1, & t_j^C(k,s) - t_j^B(k,s) > \max\left(\eta_j \cdot t_j^C(k,s), \tau_j\right) \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where $\delta_j(k)$ is a binary indicator variable that equals to 1 when driver j (with IVC capability) switches from the path currently being followed to the best alternate based on real-time and historical link travel time information, and 0 if the current path is maintained; $t_j^C(k,s)$ and

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$t_j^B(k,s)$ are, respectively, the calculated travel time value from the next node k to destination s for driver j on the path currently being followed and on the shortest path based on real-time and historical link travel time information; η_j is the relative threshold level for driver j to change from the current path to best alternate path; and τ_j is the absolute threshold level to switch from the current path to best alternate.

In the case of the binary-logit re-routing model (Equation 8), the specification involves the relative differences in total travel time and total distance between the path currently being followed and the best alternate from next decision point to its destination, together with randomly generated parameters representing each driver's familiarity with the traffic network and the resistance to change the route during the trip.

$$P_j(k,s) = \left(1 + e^{\left(\theta_1 \cdot \Delta t_j(k,s) + \Delta d_j(k,s) + \theta_3 F_j + \theta_4 R\right)}\right)^{-1} \qquad (8)$$

$$\Delta t_j(k,s) = \left(t_j^C(k,s) - t_j^B(k,s)\right) \Big/ t_j^C(k,s)$$

$$\Delta d_j(k,s) = \left(d_j^C(k,s) - d_j^B(k,s)\right) \Big/ d_j^C(k,s)$$

where $P_j(k,s)$ is the probability for driver j (with IVC capability) to switch from the current path to destination s to the best alternative shortest path at the next node k; $\Delta t_j(k,s)$ and $\Delta d_j(k,s)$ are, respectively, the relative differences in the calculated travel times and distances between the current path and best alternative path from next node k to destination s based on real-time and historical link travel time information; $d_j^C(k,s)$ and $d_j^B(k,s)$ are, respectively, the calculated travel distance from the next node k to destination s for driver j on the path currently being followed and on the shortest path based on real-time and historical link travel time information; $t_j^C(k,s)$ and $t_j^B(k,s)$ are as previously defined; F_j is a positive integer variable representing driver's familiarity with the network; R is a positive integer variable representing the drivers' (common) resistance to change their initial routes during their trips due to human being's inertia; and $\theta_1, \theta_2, \theta_3, \theta_4$ are model parameters.

In our simulation framework, each driver with IVC capability makes its re-route decision, according to two values; a probability value to change its current following path to newly found shortest path calculated from binary-logit model in Equation (8) and random value (0-1) from the random generator in the stochastic simulation process.

2.8 Performance measurements
Two broad categories of performance measurement, static and dynamic, are output from the IVC-capable vehicle dynamic on-line routing simulation studies. The static performance measurements are based on the total simulation period (excluding the warm-up period) to estimate the average performance, while the dynamic performance measurements calculate statistical results at specific time intervals (15-minute intervals in our simulation) to analyze performance changes within the time domain. Within each of these major classifications, the performance measurements are further categorized as being either traffic- or communication-

focused. Communication-focused performance measurement indices provide specification benchmarks for candidate hardware and software for real-world implementation, involving database issues, inter-vehicle communication technologies, algorithms and data structures for real-time traffic information collection and processing. Traffic-focused performance measurements are used in benefit analyses of drivers/vehicles' on-line routing behaviors based on the real-time information via vehicle-to-vehicle data sharing, both for vehicles with and without IVC equipment, and for traffic system as a whole.

Three traffic-focused performance measurement indices are derived from our simulation studies: vehicle re-route rate, average travel time for different classes of vehicles and total vehicle travel time for the whole system. Vehicle re-route rate, defined as the percentage of IVC-capable vehicles who change their routes at least once during their trips, is a measure of the population of vehicles that re-route (relative either to all IVC-capable vehicles or to all vehicles) under the influence of real-time information accessibility for specific technology parameters and traffic conditions, and under different assumptions regarding drivers' re-routing behavior. Average travel time comparisons between different groups of vehicles with and without IVC capabilities to are used to investigate potential benefits accrued from accessing real-time traffic information through peer-to-peer information exchange. The potential for accrual of benefits to the whole system (IVC- and non-IVC-capable vehicles) is captured by examining the total system travel time under the various scenarios.

3. Simulation implementations and analysis

The base simulation tool used to implement our simulation modeling framework is Paramics, a commercially available microscopic time-step traffic simulation model (Quadstone, 2004) in which each individual driver/vehicles is modeled as a driver-vehicle-unit (DVU) and updates its location in the traffic networks at every time-step. The default Paramics model does not contain any built-in modules for procedures that are required in our studies for dynamic on-line vehicle routing in the proposed information system. Using the application programming interface (API) feature of Paramics, a series of new "plug in" modules were developed in order to model IVC-capable vehicle dynamic on-line routing in the proposed information system in the simulation. They include: pre-trip static shortest path calculation and route choice behavior modules; an IVC-capable vehicle traffic information generation module; an inter-vehicle communication module; an IVC-capable vehicle information processing module; in-trip dynamic shortest path calculation and re-route behavior modules; and performance measurement modules. These new modules were integrated with the default Paramics models to dictate route choices (both before trip and during trip) under the umbrella of the proposed self-organizing, distributed traffic information system.

3.1 Simulation results for non-recurrent congestion on an arterial street grid network

The first test case concerned non-recurrent congestion scenarios in a grid network. The 5,000m × 5,000m network evaluated (Figure 4) consists of equally spaced two-lane local street roadways with speed limit of 45 mph; the distance between any two neighboring signalized intersections is 1 km. In the simulation, each direction of the roadway segments between any two intersections is further decomposed into two individual links, each 500m-long (a total of 288 one-direction links in the network).

In the scenario reported, an incident is assumed to have occurred on a link close to the center of the study grid network 15 minutes into the simulation and lasts for 30 minutes. This incident is assumed to cause passing vehicles to reduce speed to 5 mph in the direction of the roadway in which the incident occurs and to 10 mph in the opposite direction of the roadway (due to speculator slowing).

Three levels of O/D demand (shown in Table 2) are used in our simulation studies to generate light, moderate and heavy traffic flow conditions in the network; these conditions correspond to traffic volumes that, under non-incident conditions, produce Levels-of-Service (LOS) A, C, and E, respectively.

Table 2. O/D Demands for Grid Arterial Street Network

O/D Demand Level	Average Speed (mph)	Density (vehicles/kilometer)
Light	25	20
Moderate	17	42
Heavy	10	68

The total simulation time is 1 hour; and the first 15 minutes are used as "warm-up" in the simulation; statistical calculations for simulation output results are for the final 45 minutes of the simulation only. For each unique input parameter combination, 30 different random seeds are used in the simulation studies, and the average of all results is used for analysis.

Because of the multiplicity of routes between origin/destination pairs in this grid network, the random-arbitrary method is used to generate two groups of link travel time values for each individual link in the network, and two shortest paths are calculated based on these link travel time values for each origin/destination pair. According to the binary-logit route choice model presented in Equation (4) and the random generator in the simulation, each vehicle was then assigned to one path from these two calculated paths from its origin to its destination as its initial, "pre-trip," path.

In the simulation, vehicles without IVC capability follow their initial paths from their origins to their destinations, unaltered due to their inaccessibility to real-time traffic information. Alternatively, each individual IVC-capable vehicle acts as a polling vehicle in the traffic network to collect both link travel time information (based on either full or partial experience on the links it travels) and incident information, exchanges link-based information packets with each other through the IVC system, and updates the shortest route from current location to its destination based on the newest link travel time information and historical link travel time information from historical traffic information database loaded within vehicles. At each decision point along its path, the rational-boundary model in Equation (7) is implemented for each IVC-capable vehicle's re-routing decision and the vehicle switches to the new shortest path if it differs from its current path.

Based on these simulations, three traffic-related performance measurements were calculated: 1) re-routing rate for IVC vehicles (relative both to all IVC-capable vehicles and to all vehicles in the network) whose initial paths include the link (for either direction) on which the incident occurs, 2) average vehicle travel times for incident-impacted vehicles (both for IVC- vehicles vs. non-IVC-vehicles and for vehicles that reroute during their trips vs. vehicles that do not), and 3)

total vehicle travel time for the whole system. Results of these performance measurements are shown in Figures 5 through 9.

Shown in Figures 5 and 6 are re-routing rates for IVC-capable vehicles whose initial paths include the link (in either direction) on which the incident occurs. Figure 5 presents these results relative to the population of IVC-capable vehicles; Figure 6 relative to the total population of vehicles. As expected, the rates increase with IVC market penetration rate and communication radius range under all traffic conditions considered, since that the former results in more IVC-capable vehicles acting as polling vehicles in the traffic network while the latter results in an increase in the extent of the two-dimensional grid roadway network that can be reached through inter-vehicle information exchange. The greater the frequency with which raw traffic information is generated and the faster the information propagation the easier it is for each IVC-capable driver to estimate real-time traffic conditions in time to take advantage of re-routing options to escape heavy congestion locations affected by the incident.

Shown in Figure 7 are results for average travel time comparisons between IVC- and non-IVC-capable vehicles whose initial paths include the link (in either direction) where the incident occurs. The results indicate that the IVC-capable vehicles require less time to complete their trips than do vehicles restricted to following their initial paths for all demand levels considered when the IVC market penetration rates are higher than a threshold value of approximately 1%–2%. Consistent with the observations noted above regarding the correlation of rerouting rates with market penetration and communications range, we find similar correspondence for the relative travel time saving values for re-routed IVC-capable vehicles vs. vehicles without re-routing behavior. However, because of the increasing number of IVC-capable vehicles taking re-routing actions under higher IVC market penetration rates, the marginal benefits accrued by IVC-capable vehicles re-routing can decrease with increasing market penetration (and even decrease in absolute terms) as shown in these figures; as greater numbers of vehicles migrate from their initial paths to preferred paths, thereby both decreasing the performance of the paths to which they re-routed while lessening the impact of the incident on the paths they vacated (which includes the link on which the incident occurs). This result is consistent with those found by other researchers in assessing the "optimal" information penetration rate for system performance.

Since only IVC-capable vehicles have capabilities to dynamically navigate based on real-time traffic information, it is intuitive that travelers with IVC have a travel time advantage over travelers without IVC capabilities; this presuming that there is sufficient opportunity for IVC interaction. As shown in Figure 8, only when IVC market penetration rates are higher than some threshold values (roughly around 2%, but which vary for different communication radius ranges and demand levels) is the average travel time for IVC-capable vehicles generally less than that for non-IVC vehicles. Near these threshold values, there is a compensatory relationship between market penetration and communications range. Expectedly, travel time savings for IVC-capable vehicles compared to non-IVC vehicles increase with higher IVC market penetration rates and longer communication radius range until reaching maximal values, and then decrease as the increasing re-routing results in reduced marginal benefit.

Figure 9 presents performance results for the whole traffic system, including travelers with and without IVC capability. Beyond thresholds for market penetration rates and communication range identified above, total vehicle travel time decreases with increasing penetration and communications range for all traffic demand levels considered. This is an outcome of the IVC-capable vehicles' travel time savings from re-routing and the travel time savings for non-IVC

vehicles whose paths include the incident link (now with less demand as a result of IVC-capable vehicles re-routing) being greater than the increased travel time on the links comprising the IVC-capable vehicles' re-routing paths. Under heavy demand levels, reduction in unused network capacities needed to accommodate IVC-capable vehicles in their re-route paths produces less dramatic system performance improvements.

In summary, several interesting results are obtained from our simulation studies under non-recurrent congestion scenarios in the grid arterial streets network. First, only when IVC market penetration rate is higher than some threshold values, can IVC-capable vehicles make sufficiently accurate estimations of real-time traffic conditions to take re-routing actions. This threshold value is relatively high compared to freeway networks (as we will show in the next subsection) due to the dimensional characteristics of grid arterial networks compared to freeways (Yang, 2003). Although the relative travel time saving benefits for IVC-capable vehicles from re-routing decrease after reaching maximum values, IVC-capable vehicles always maintain an advantage compared to their counterparts and total system performance improves by their re-routing. The explanation for this result comes from two asspects: 1) in the pre-trip route choice behavior model implemented for this grid arterial streets network, each vehicle (IVC-capable or non-IVC) can select the path from its origin to destination from a set of only two possible choices, and 2) in this particular grid test network, multiple similar route choices exist between each origin and destination, and each individual link in the network has a similar capacity. Since there are only two selectable choices in the simulation from possible multiple routes (mostly more than two) from each origin to destination, neither system optimum nor user equilibrium can be achieved generally under these conditions. Moreover, both may never to be truly achievable in real-world transportation systems; however, the simulation results indicate that re-routing behavior enabled by IVC can move performance toward system optimal.

3.2 Simulation results for non-recurrent congestion on a freeway corridor network

The second test case considers non-recurrent congestion scenarios along a freeway corridor with a neighboring alternative arterial street. The test network is comprised of an 8-lane freeway with 4 lanes in each direction and speed limit of 65 mph, and a 4-lane arterial street parallel to the freeway with 2 lanes in each direction and speed limit of 45 mph. The 8-lane freeway and 4-lane arterial are each 20 km long; the distance between the freeway and its alternative parallel arterial streets is 1.5 km. Both freeway and arterial streets are segmented into 500-meter long links. The freeway and parallel arterial street are connected by other arterial streets running perpendicular to the freeway and freeway on/off ramps spaced at 2000-meter intervals. Figure 10 shows a sketch of this network.

In the simulation, an incident 4000 meters from the far end of the network occurs 30 minutes into the simulation and lasts for 30 minutes; owing to the blockage caused by the incident, vehicle speed in that direction is reduced to 5 mph near incident location. (See Figure 10 for details). Three levels of O/D demand (shown in Table 3) are used to generate light, moderate and heavy traffic flow conditions (corresponding to LOS A, C, and E, respectively), both for the freeway and the arterials.

Table 3. O/D Demands for Freeway Corridor Network

O/D Demand Level	Freeway Mainline Flow Rate (vehicles/hour)	Arterial Streets Flow Rate (vehicles/hour)
Light	3000	500
Moderate	6000	750
Heavy	9000	1000

The time period simulated varies for different levels of O/D demand, based on the time needed to clear the traffic jam and return traffic conditions back to normal after the incident: 1 hour and 15 minutes for light traffic conditions, 1 hour and 30 minutes for moderate traffic conditions, and 1 hour and 45 minutes for heavy traffic conditions. As in the previous case, the first 30 minutes of the simulation is treated as a "warm-up" time period; statistical calculations are only for the time period following this warm-up period. For each unique input parameter combination, 30 different random seeds are used in the simulation studies, and our analysis is based on the average of all results.

During the pre-trip planning phase, routes are selected based upon the shortest path between each origin/destination pair, calculated using the experience-average method for generating the historical traffic information database. All drivers (with and without IVC capabilities) from the same origin to the same destination choose the same calculated shortest path from that specific origin to that specific destination as their initial path. During their trips, IVC-capable vehicles generate link-based travel time information packets based on their own experiences, exchange information packets among themselves, process that traffic information in real-time and re-compute shortest paths based on their viewpoint of current traffic conditions and from historical traffic patterns. Re-routing decisions may be made for each individual IVC-capable vehicle, according to the calculated probability value from in-trip re-route binary-logit model specified by Equation (8) and a random number generated by the simulation at every decision point.

Re-routing rates for IVC-capable vehicles (relative to all vehicles), who are either directly (i.e., routes contain links on which the incident occurs) or indirectly (i.e., routes contain links that are impacted either by spillback or re-routed traffic) affected by the incident on the freeway, increase with higher IVC market penetration rates and longer communication radius ranges under all traffic conditions, as shown in Figure 11. Although in absolute numbers more vehicles with IVC capability re-route during their trips as IVC market penetration rate and communication ranges increase, re-route rates for IVC-capable vehicles as a percentage of all IVC-capable vehicles decrease after reaching a maximal value, as shown in Figure 12. While increasing values of IVC market penetration rate and communication range generally result in more frequent raw traffic information generation and faster information propagation, ostensibly provide each driver with IVC capability greater opportunity to identify alternative paths with less congestion, the greater percentage of IVC-capable vehicles acting on this information produces fewer and fewer benefits for re-routing due to worsening of traffic conditions on their possible re-routing paths. Consequently, there is asymptotic behavior among IVC-capable drivers as the marginal benefits of re-routing lower to some limit.

Figures 13 and 14 show results for average travel time comparisons between all IVC-capable vehicles (Figure 14), the subset of IVC-capable vehicles that re-routed (Figure 13) and non-IVC-

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capable vehicles traveling either on the freeway or arterial streets in the direction impacted by the incident. The results indicate that the re-routed IVC-capable vehicles generally (and expectedly) take less time to complete their trips than do vehicles confined to their initial paths; this result holds for all demand levels when the IVC market penetration rates are higher than a threshold value (approximately 0.2–0.5%; Figure 14), except for the combination of heavy demand and high market penetration (0.20). Results shown in these figures also indicate that the relative travel time savings for re-routed IVC-capable vehicles continuously increase with IVC market penetration rate and communication range to maximal values, decreasing thereafter. These results stem from the opposing effects of better and faster traffic condition estimation with which to optimize new routes with the higher IVC market rates and longer communication ranges and the deterioration of traffic conditions on possible alternative paths due to re-routed traffic (and the corresponding improvement on the initial paths resulting from the diversion).

Total system performance as measured by the vehicle travel time for all vehicles potentially impacted by the incident over the entire simulation period (excluding the warm-up period) is shown in Figure 15. The results indicate that the impact of the real-time information provided IVC-capable vehicles is greatest under conditions of light to moderate traffic, during which there is sufficient excess system capacity to redistribute impacted IVC- vehicle traffic in a manner that moves the entire system toward system optimal conditions. Even at the higher IVC market penetration rates and longer communication ranges under light and moderate demand levels the travel time savings from re-routing is larger than the increase in travel time for vehicles not directly affected by the incident owing to the worsening of traffic conditions on the arterial streets on the re-routing paths. However, under heavy demand, less unused capacity exists on the arterial streets to accommodate re-routed vehicles, and system performance is not noticeably better and actually can become worse with high IVC market penetration rates and long communication ranges, as seen in Figure 15.

Several results from the simulation of dynamic on-line routing under non-recurrent congestion scenarios in the freeway corridor network differ from the grid arterial streets network cases. First, the threshold values for effectiveness of IVC is lower in freeway corridor network cases as compared to the grid arterial streets network. Even under the lower IVC market penetration rates, traffic information dissemination along the freeway is greatly assisted by IVC-capable vehicles' movements in opposing lanes of the freeway, and the "coverage" is universal in the sense that even a single vehicle will generally come in contact with every other IVC-capable vehicle in the lanes upstream of an incident. By way of contrast, in the two-dimensional grid arterial streets network, the intersection of any two IVC-capable vehicles' communication range is a function of the paths taken by the respective vehicles, which are distributed in two-dimensional space rather than being confined to a single, linear, path that virtually ensures the opportunity to communicate with opposing traffic.

For most cases in the freeway corridor network, as increasing numbers of drivers have accessibility to real-time traffic information from inter-vehicle information exchange, the redistribution of IVC-capable vehicles enables the system to move toward user equilibrium. The characteristics of this freeway corridor network are such that a traveler has significantly fewer choices than in the grid arterial streets network (actually only having two basic choices—taking either the freeway or arterial streets from its origin to destination). Under normal traffic conditions the freeway system typically has much more capacity and a better level of service than its surface street alternative, leading to many more vehicles choosing to use the freeway

system under these conditions; thus, even a relatively small amount of IVC-capable vehicles' re-routing from the freeway to arterial streets may dramatically worsen the traffic conditions on the arterial streets, resulting in a general worsening of system performance under heavy demand.

4. Summary and Conclusions

Although dynamic on-line routing based upon advanced traffic information systems has been studied by researchers dating back to 1990, attention has been focused on centralized systems. Alternatively, the focus of this article is on modeling dynamic vehicle navigation in a self-organizing, distributed traffic information system built on vehicle-to-vehicle information exchange among these vehicles. A micro-simulation modeling framework is built to study IVC-capable vehicles dynamic on-line routing behavior in the self-organizing, distributed information system, incorporating efforts to model: 1) the historical traffic information database, 2) drivers' pre-trip route choice behavior, 3) in-trip raw traffic information generation from IVC-capable vehicles, 4) information exchange among IVC-capable vehicles, 5) information processing within each IVC-capable vehicles, 6) IVC-capable vehicles' in-trip route optimization, and 7) re-routing behavior of drivers with IVC capabilities.

In our simulation modeling framework, two methods—random-arbitrary method and experiences-average method—are used to calculate link travel time values from which shortest paths from each origin to each destination are found that comprise the historical traffic information database. Drivers' pre-trip route choices are modeled according to either a pre-trip binary logit model or simply based on shortest-path selection in their trip planning phases. A path-based microscopic traffic simulation model is constructed to model vehicle navigation in the traffic network. During its trip, each IVC-capable vehicle generates link travel time information embedded in traffic information packets from its own full or partial traveling experience, following a roadway traffic condition sampling policy that combines both a time basis mode and a link basis mode. A modified exponential filter is used to smooth raw link travel time values to estimate current traffic conditions after each IVC-capable vehicles receives link-based information packets from any neighboring IVC-capable vehicles through peer-to-peer information exchange. In the simulation, each IVC-capable vehicle optimizes its own path based on its estimate of current traffic conditions and historical recurrent traffic congestion information, taking re-routing actions according to either a rational boundary model or binary logit model.

The efficacy of IVC is tested on two networks—grid arterial streets network and freeway corridor network—under conditions representing non-recurrent congestion scenarios under various demand levels. Results from these cases show the conditions under which travelers with IVC equipment capable of accurately estimating real-time traffic conditions can be expected to achieve time-savings through dynamically optimizing their paths based on the historical and current information in such self-organizing, distributed traffic information systems. Except under heavy demand levels for the freeway corridor network, overall system performance is shown to improve with IVC-capable vehicles dynamic on-line re-routing as IVC market penetration rate and communication range increase. The results indicate that a self-organizing, distributed traffic information system built upon autonomously polling of vehicles as a means for traffic surveillance has the potential to not only bring benefits to travelers within the IVC information system, but also to benefit the traffic system as a whole in most cases.

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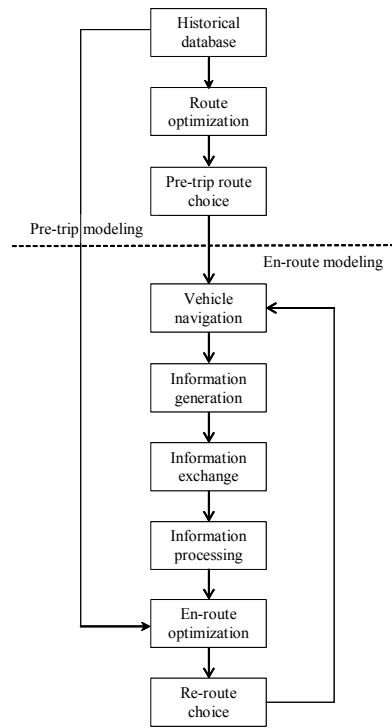
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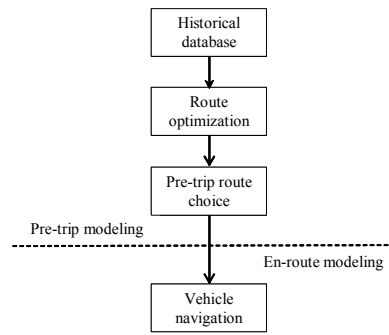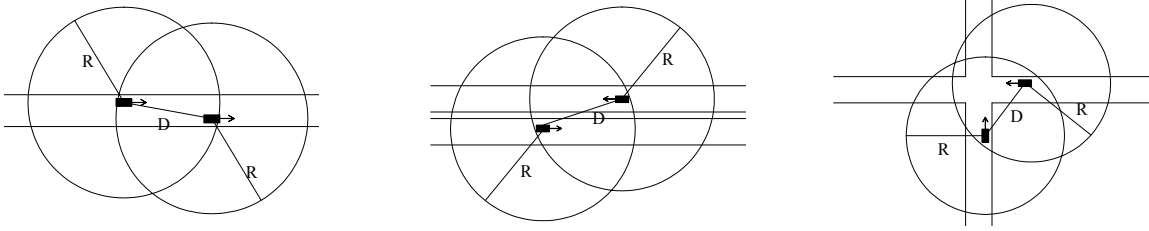
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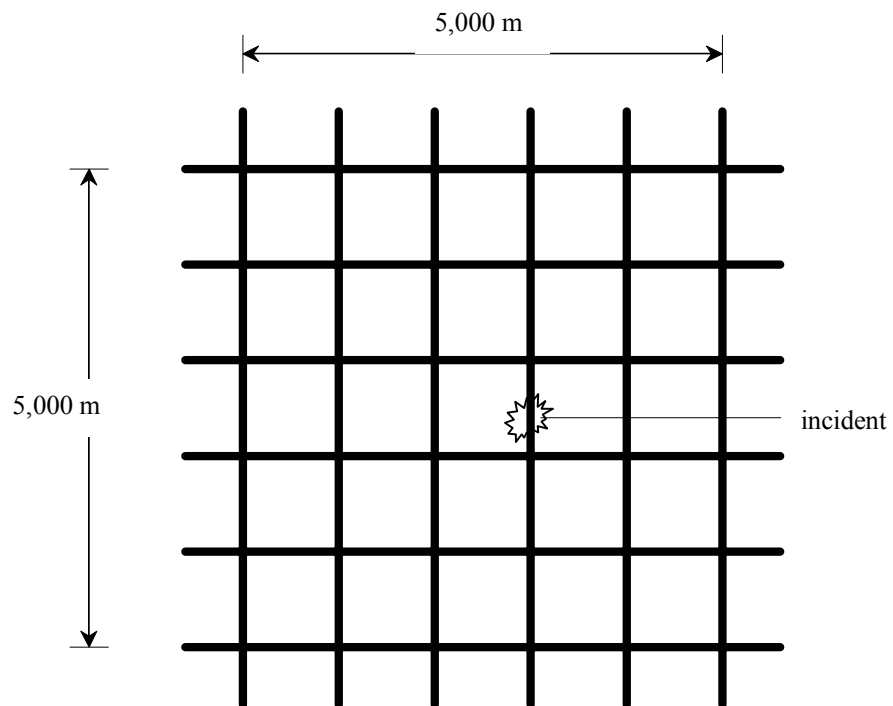
Figure 4. Grid arterial streets test network
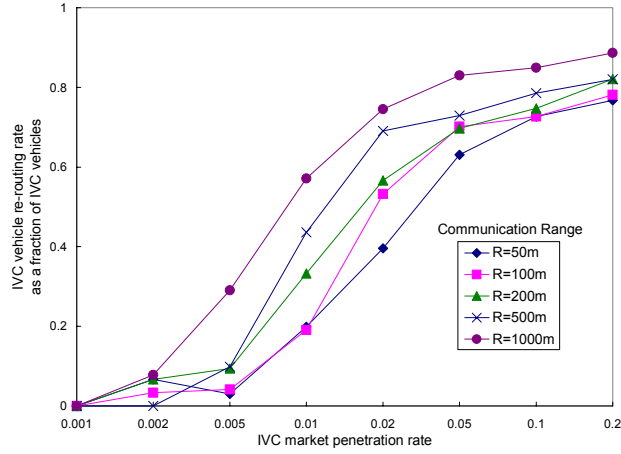
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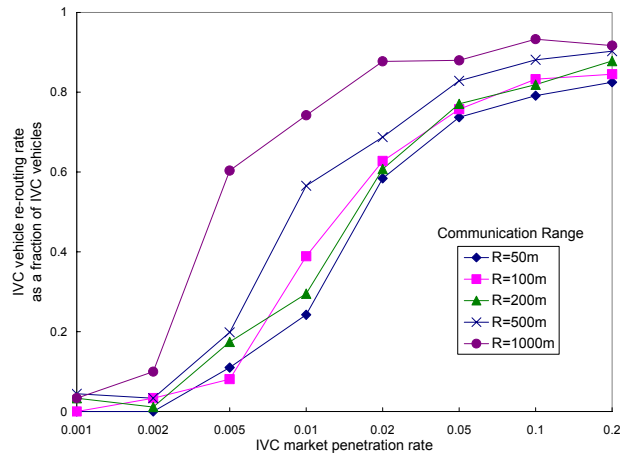
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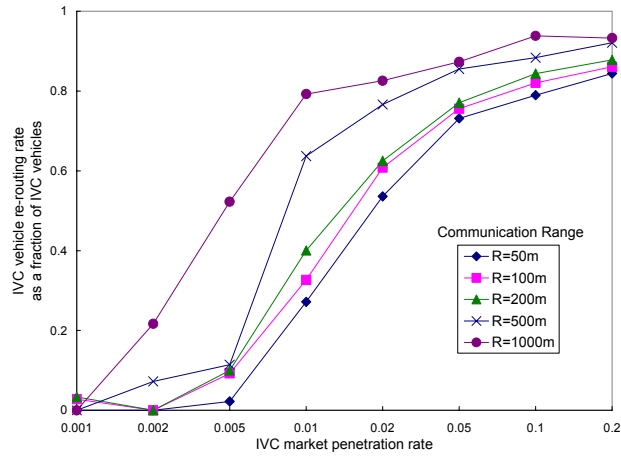
Figure 5c. Heavy Traffic

Figure 5. IVC Re-routing Rate Relative to IVC Vehicle Population
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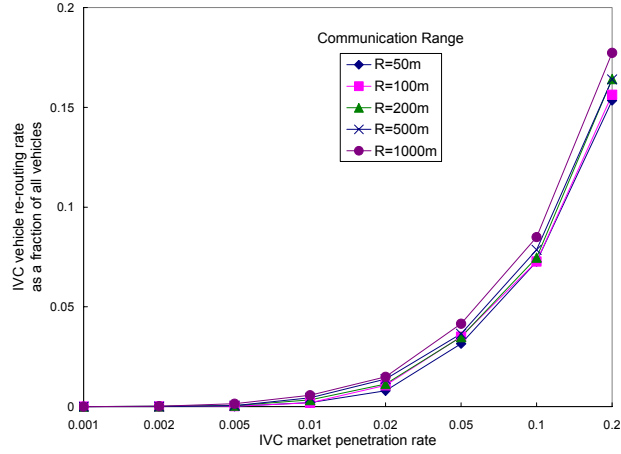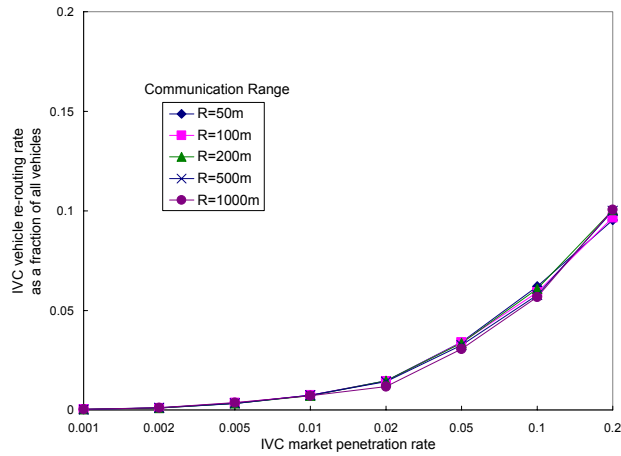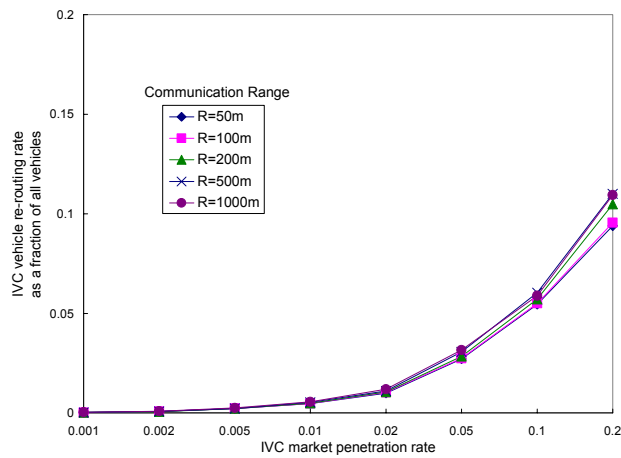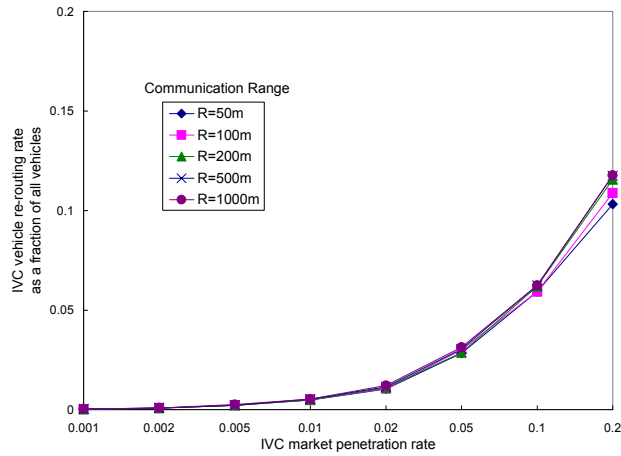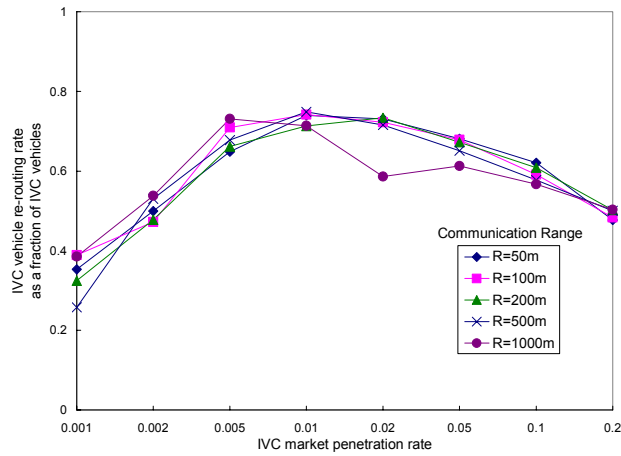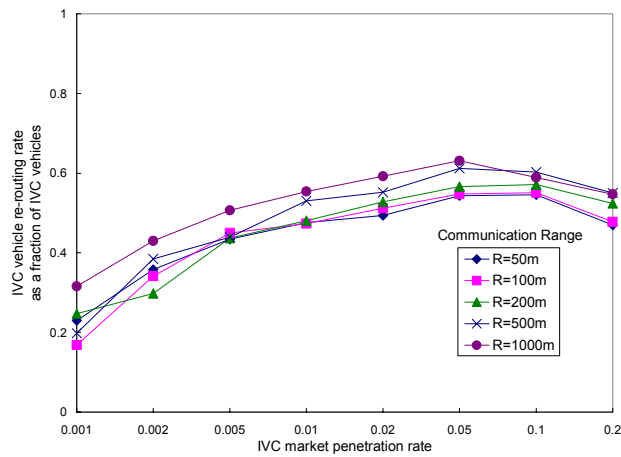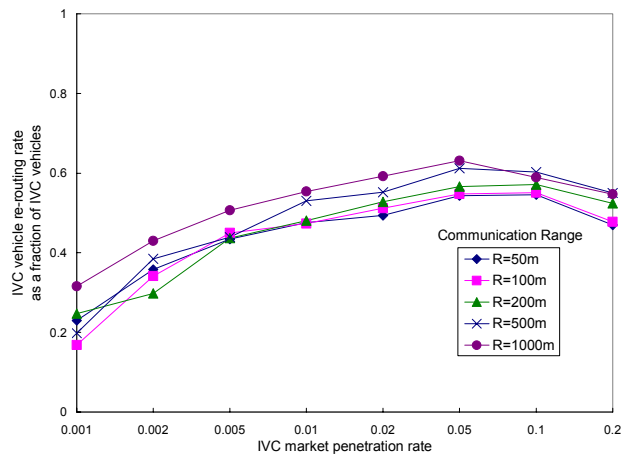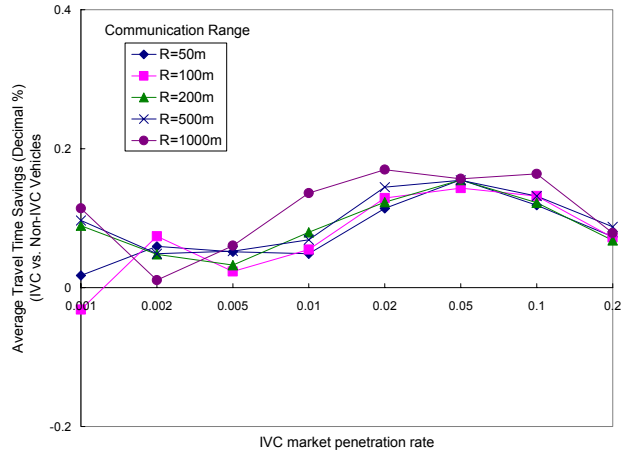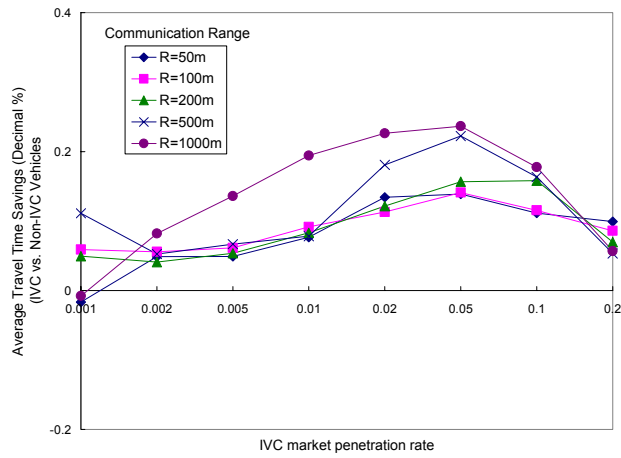
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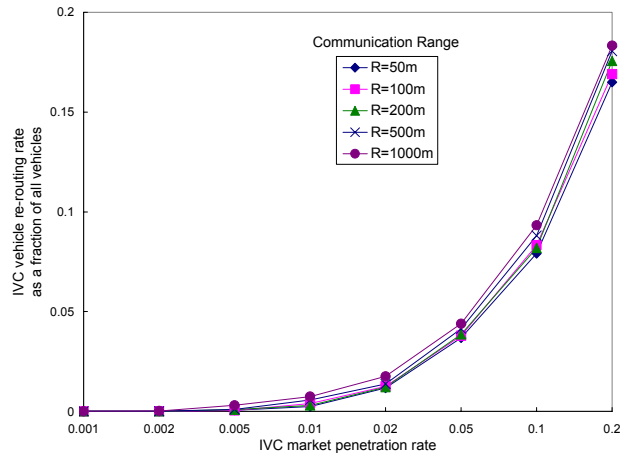
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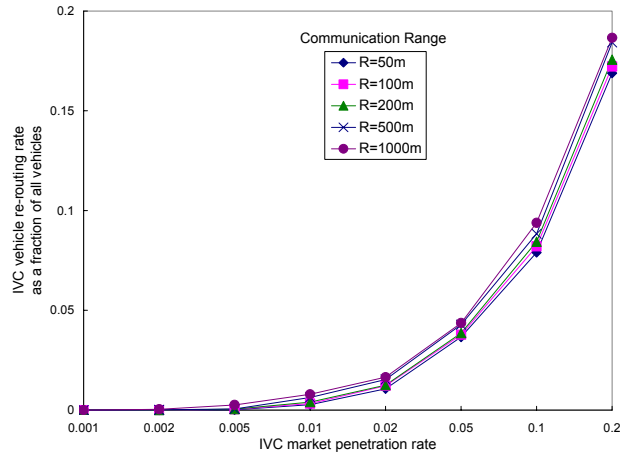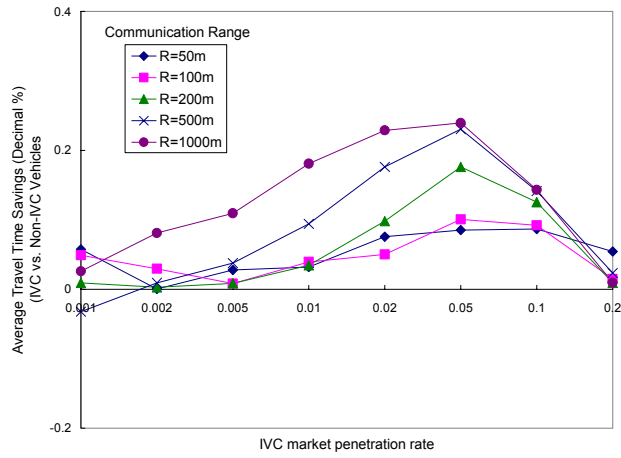

Figure 6c. Heavy Traffic

Figure 6. IVC Re-routing Rate Relative to Total Vehicle Population
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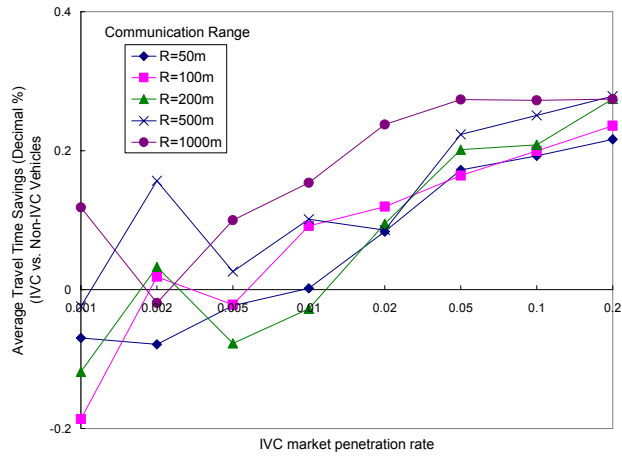
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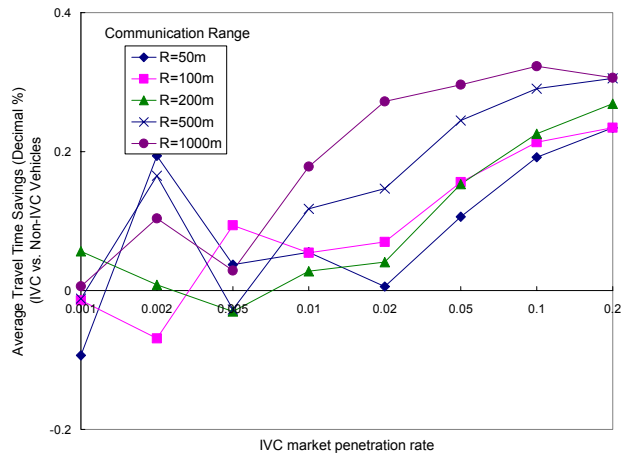
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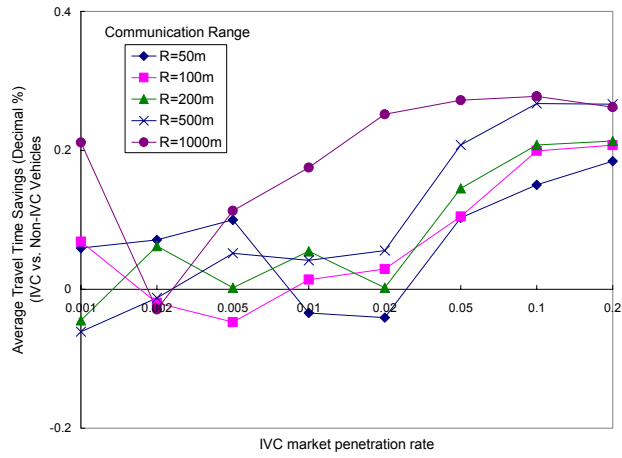
Figure 7c. Heavy Traffic

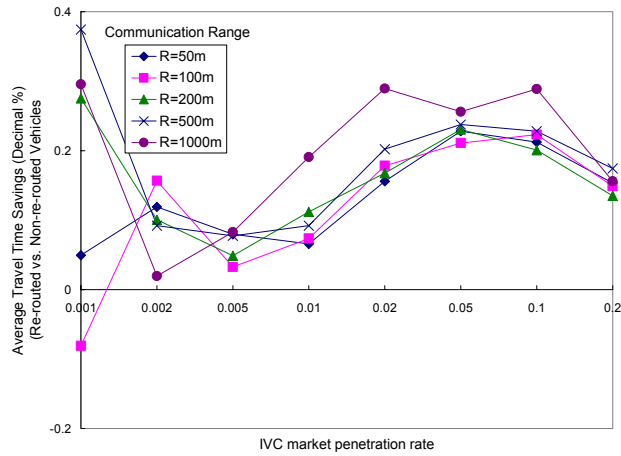Figure 7. Relative Time Savings of IVC Vehicles
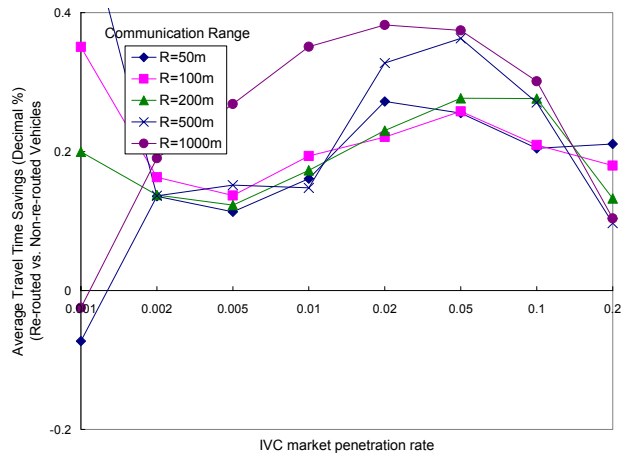(Grid Network)
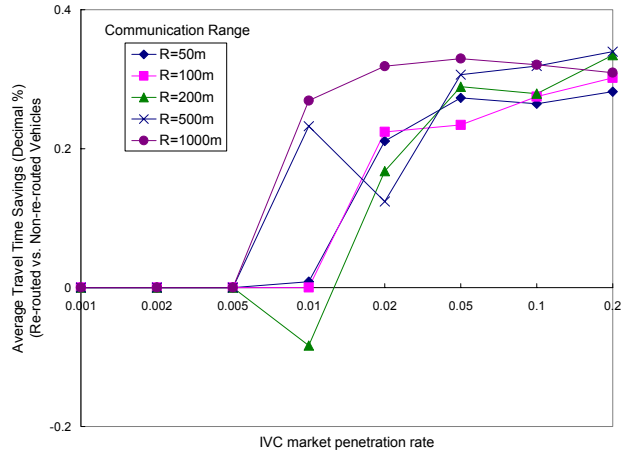
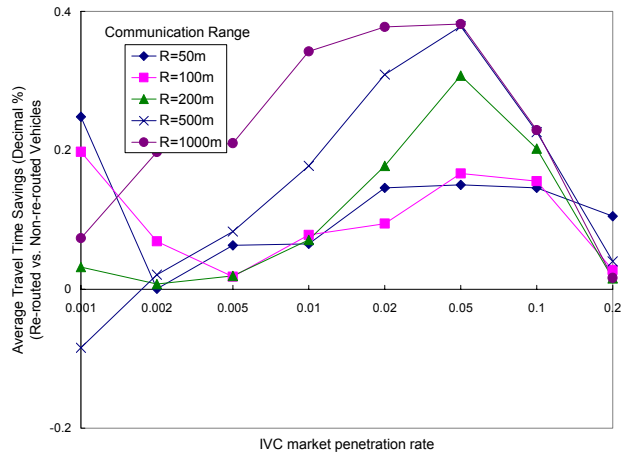Figure 8a. Light Traffic
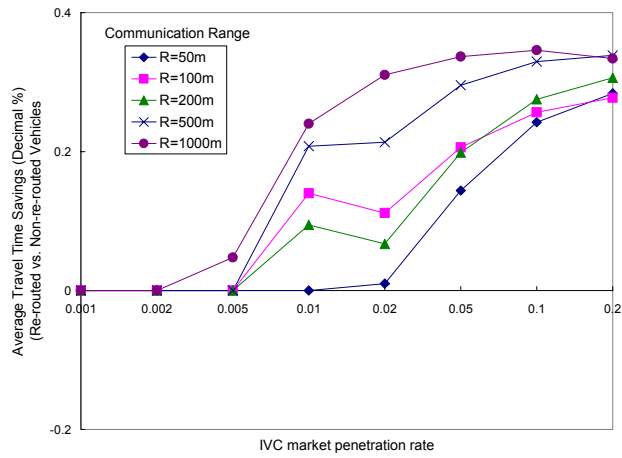
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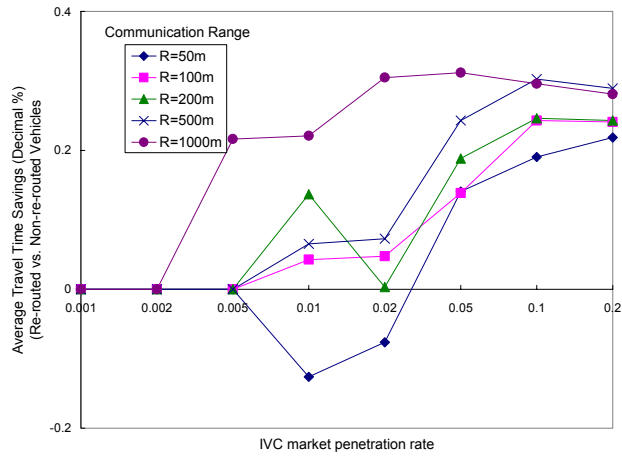
Figure 8c. Heavy Traffic

Figure 8. Relative Time Savings of Re-routed IVC Vehicles
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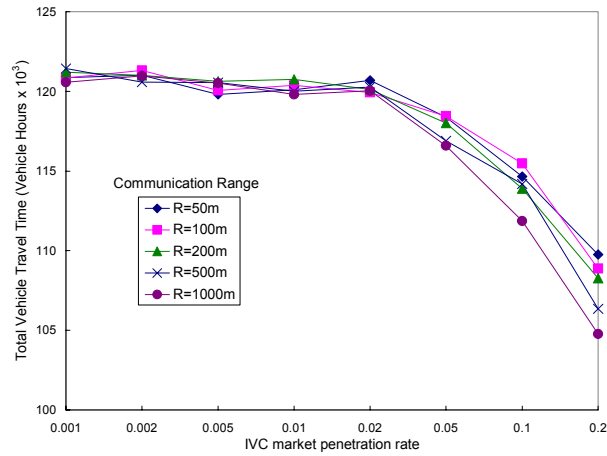
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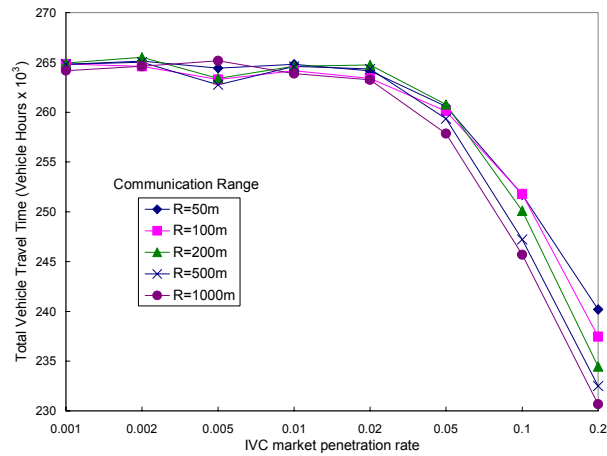
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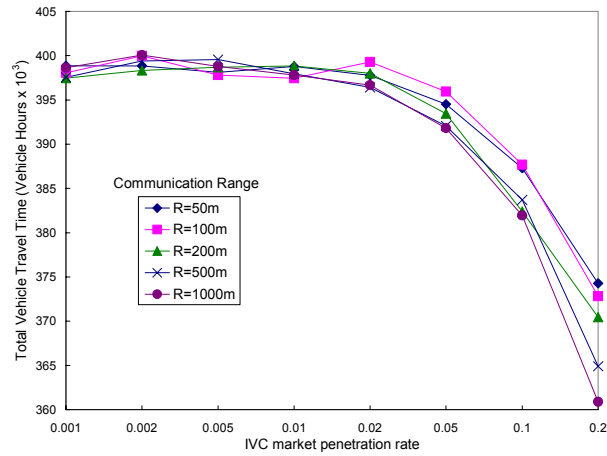
Figure 9c. Heavy Traffic

Figure 9. Impact of IVC on Total System Travel Time
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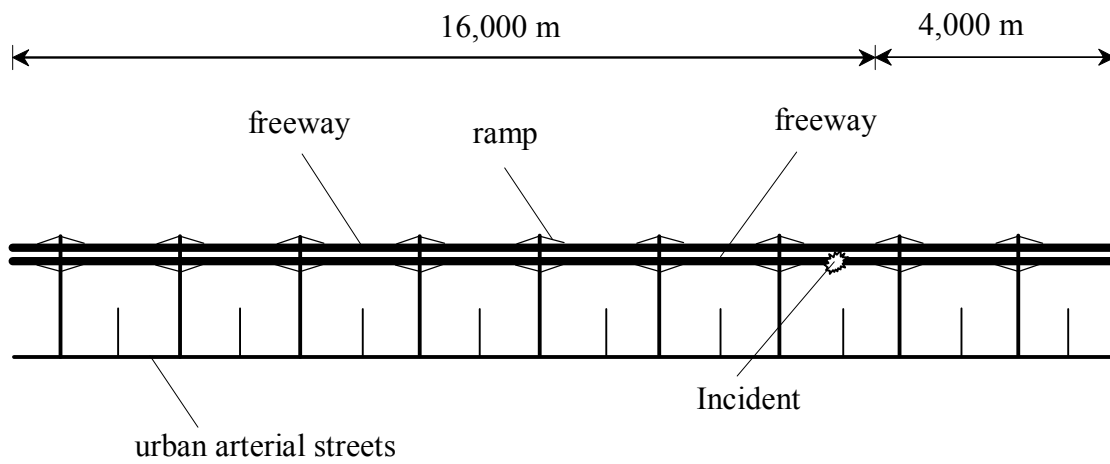
Figure 10. Freeway Corridor Test Network

Figure 11a. Light Traffic

Figure 11b. Moderate Traffic

Figure 11c. Heavy Traffic

Figure 11. IVC Re-routing Rate Relative to Total Vehicle Population
(Freeway Network)

Figure 12a. Light Traffic

Figure 12b. Moderate Traffic

Figure 12c. Heavy Traffic

Figure 12. IVC Re-routing Rate Relative to IVC Vehicle Population
(Freeway Network)

Figure 13a. Light Traffic

Figure 13b. Moderate Traffic

Figure 13c. Heavy Traffic

Figure 13. Relative Time Savings of IVC Vehicles
(Freeway Network)

Figure 14a. Light Traffic

Figure 14b. Moderate Traffic

Figure 14c. Heavy Traffic

Figure 14. Relative Time Savings of Re-routed IVC Vehicles
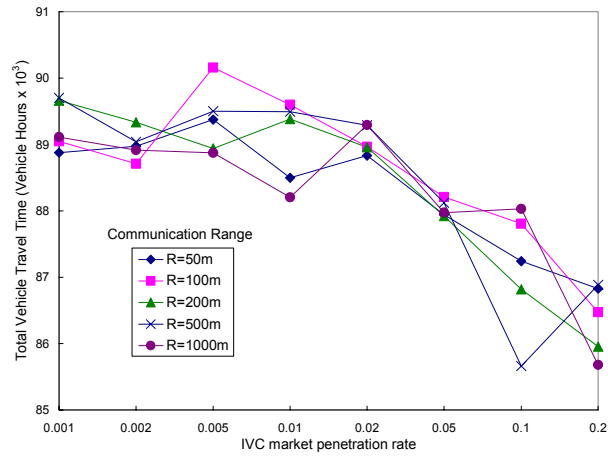(Freeway Network)
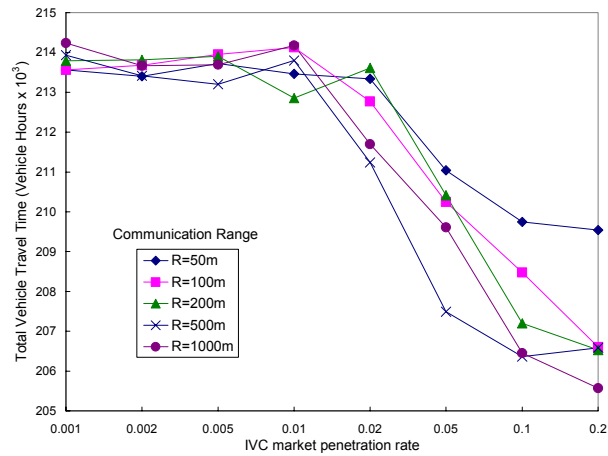
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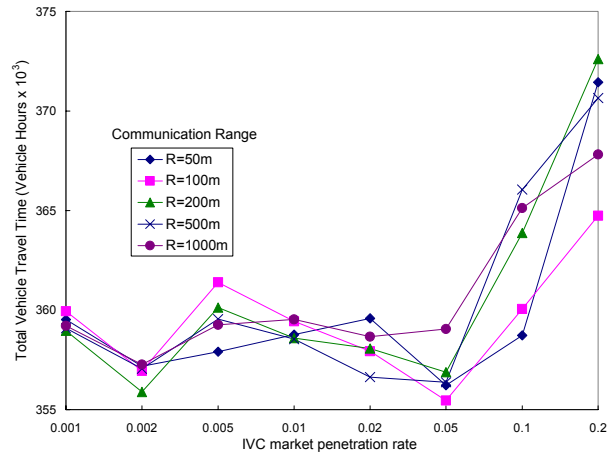Figure 15b. Moderate Traffic

Figure 15c. Heavy Traffic

Figure 15. Impact of IVC on Total System Travel Time
(Freeway Network)